Geneva, 8 February, 2012

M E M O R A N D U M

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Subject: protection estimates for the 13 kA bus bars interconnections at 3.5 - 4.5 TeV

This memorandum provides alternate estimates of the critical additional resistance R_{add} of the 13 kA superconducting bus bars interconnections (IC), both for the LHC main bending (MB) dipole and main quadrupole (MQ) magnets. The calculations are performed using the 1-D thermo-electrical model described in [1], based on the definition of transverse local heat transfer coefficient towards the cooling helium bath established from the analysis of short sample tests performed in 2009 and 2010. Details on the model and its validation are not discussed here. The most pessimistic (adiabatic), most optimistic (full cooling) and most likely (partial cooling) critical additional resistances are provided, depending on the bus-bar and cable RRR, dump time constant, and space distribution of the defect, for beam energy between 3.5 and 4.5 TeV.

Tables I and II summarize the critical additional resistances at room temperature R_{add}. Table I refers to the IC of the MB magnets bus, whereas Table II to the IC of the MQ magnets bus. Current dump time constants of 52 s (MB) and 10 s (MQ) correspond to acceptable dump voltage up to 4 TeV (used in 2010 and 2011). Longer dump time constants for 4 or 4.5 TeV [2] are considered to demonstrate the effect of a further energy increase in 2012 [3].

For each pair of beam energy and current decay time constant τ_{dump} reported in the first two columns of Tables I and II, the critical additional resistances are reported in the following columns under various hypotheses of cooling. Indeed, heat transfer from a quenching IC has a proven importance, but contains a residual uncertainty in the value of the heat transfer coefficient (HTC). Values of HTC through the bus bar insulation towards the 1.9 K He bath were obtained through dedicated measurements [4], while values of HTC through the IC insulation was addressed in [5], obtaining a good agreement with the experimental measurements and showing that the interconnection region cannot be considered adiabatic. It must be said, however, that further investigations would be needed to completely describe it. Consequently, we have considered three heat transfer conditions, of which the middle one is considered the one closest to reality:

- fully adiabatic case, to compare with previous analyses, representing the most pessimistic evaluation (third column in Tabs. I and II);
- the case of adiabatic interconnection and He II cooled bus bar (fourth column in Tabs. I and II), that can be seen as a reasonably conservative lower limit;
- the case of bus bar HTC assumed for the whole sample length, i.e. in the IC as well (fifth column) which is an optimistic evaluation and is reported here only for information.

As mentioned earlier, the cable and bus bar *RRR* values as well as the spatial distribution of the excess resistance were considered as parameters in the analysis. The first part of Tables I and II assumes the conservative hypothesis of a soldering defect confined to one side of the IC, and the smallest *RRR* values of the ranges investigated in [1]: RRR_{cable} = 80, RRR_{bus} = 100. The second part is based on the most optimistic investigated hypotheses, i.e. a soldering defect equally split on the two sides of the IC, and the highest assumed *RRR* values: RRR_{cable} = 160, RRR_{bus} = 220. It is worth noting that the reported computations refer to a resistive transition originating at the interconnection under the assumptions of the mentioned model. Other scenarios were not considered.

MB

	Beam energy [TeV]	**τ_{dump} [s]**	**Adiabatic everywhere**	**Adiabatic IC, bus HTC elsewhere**	**bus HTC everywhere**
				R_{add} [μΩ]	
$RRR_{cable/bus}$ = 80/100 Single Defect	**3.5**	**52**	53	82	118
	4	**52**	43	66	91
	4	**68**	38	66	90
	4.5	**68**	30	64	73
$RRR_{cable/bus}$ = 160/220 Double Defect 50-50 %	**3.5**	**52**	125	151	464
	4	**52**	97	122	312
	4	**68**	82	110	305
	4.5	**68**	66	90	230

Table I. Estimates of the MB critical additional resistance.

MQ

	Beam energy [TeV]	τ_{dump} [s]	Adiabatic everywhere	Adiabatic IC, bus HTC elsewhere	bus HTC everywhere
				R_{add} [μΩ]	
$RRR_{cable/bus}$ = 80/100 Single Defect	**3.5**	**10**	69	79	136
	4	**10**	53	64	94
	4.5	**10**	43	52	73
	4.5	**12**	42	51	71
$RRR_{cable/bus}$ = 160/220 Double Defect 50-50 %	**3.5**	**10**	183	278	615
	4	**10**	142	192	356
	4.5	**10**	114	151	253
	4.5	**12**	104	139	247

Table II. Estimates of the MQ critical additional resistance.

The values reported above deserve a few comments:

- MB and MQ limits obtained in adiabatic conditions, low cable/bus RRR (80/100), for single-sided defect are comparable to those quoted in previous analyses (R_{add} = 43 μΩ for MB at 4 TeV);
- An increase of the cable/bus RRR (160/220) to the values measured (bus) or expected (cable) in the LHC, and considering a soldering defect distributed in the IC, yields an increase of the acceptable value of R_{add} by more than a factor 2 (R_{add} = 97 μΩ for MB at 4 TeV);
- Assuming conservative values for the cable/bus RRR (80/100) and single-sided defect, but considering realistic values for the heat transfer from the bus to the helium, yields a 50 % increase of the acceptable value of R_{add} (R_{add} = 66 μΩ for MB at 4 TeV);
- An increase of the dump time constant does not have a large effect on R_{add} in the conditions analysed (quench initiated at the IC), especially when considering the case of a cooled bus.

In conclusion, it seems that a critical analysis of the data collected in the dedicated IC tests performed in 2009 and 2010, and the confirmation of higher Copper RRR in the bus-bars, indicate that the assumption taken for the decision on operation at 3.5 TeV are quite conservative, and may be relaxed.

References

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[2] K. Dahlerup-Petersen, private communication, 2011.

[3] S. Myers, F. Zimmermann, "Chamonix '11 Summary: Proposals for Decisions", *Proceedings of the Chamonix 2011 Workshop on LHC performance*.

[4] P.P. Granieri. M. Casali, D. Richter, "Heat Transfer in the LHC Main Superconducting Bus Bars", *Proceedings of ICEC 23 – ICMC 2010*, Wroclaw, Poland, pp. 411-416, 2010.

[5] P.P. Granieri, M. Casali, M. Bianchi, M. Breschi, L. Bottura, G.P. Willering, "Analysis of Defective Interconnections of the 13 kA LHC Superconducting Bus Bars", accepted for publication on *IEEE Trans. Appl. Sup.*.